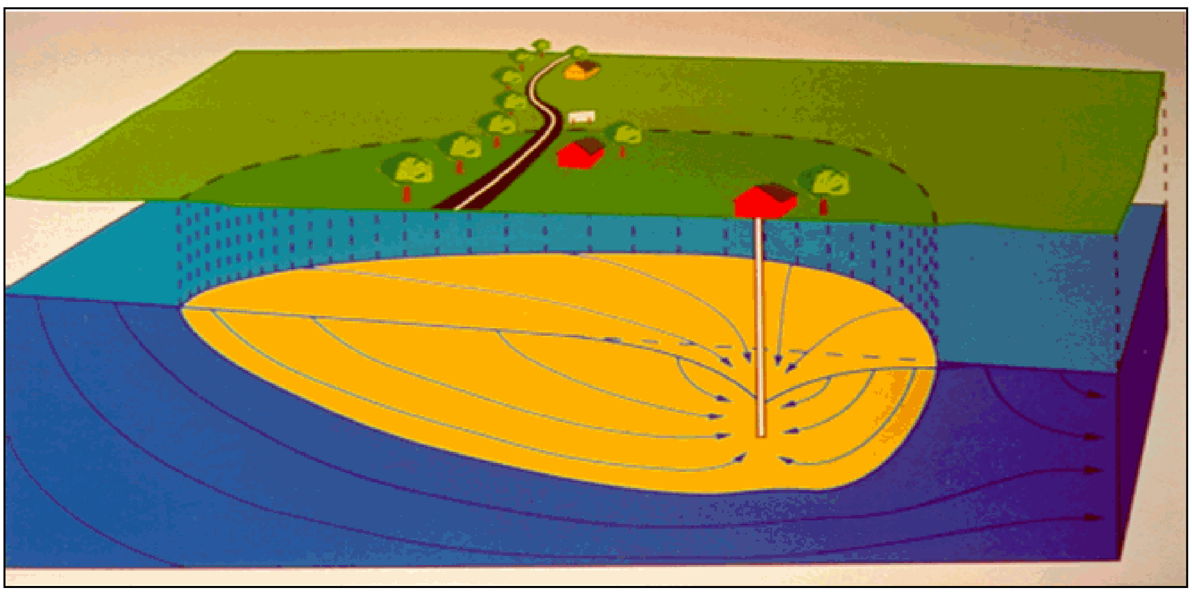
# Drinking Water Source Protection Area Delineation Guidelines and Process Manual



Division of Drinking and Ground Waters
Source Water Assessment and Protection Program
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# DRINKING WATER SOURCE PROTECTION AREA DELINEATION GUIDELINES & PROCESS MANUAL

## 1.0 INTRODUCTION

As part of Ohio's Source Water Assessment and Protection Program (SWAP), Ohio EPA has developed process manuals for completing the three steps necessary to complete a source water assessment for each public water system (PWS) in the state that uses ground water as its primary source of drinking water. The three steps in a source water assessment for public water supplies using ground water are:

1) Delineate the area from which a public water supply receives its water (SWAP area);
2) Inventory potential significant contaminant sources within the SWAP area; and
3) Determine the susceptibility of the source water (aquifer) to contamination.

All of these components of a source water assessment will be completed by Ohio EPA or an Ohio EPA contractor (with the assistance of the public water supplier) unless portions of the assessment have already been or are in the process of being completed by the public water system. The purpose of completing the source water assessment is to provide information that each PWS can use to develop a plan to protect their drinking water supply from contamination. The development of a source water protection plan is strongly recommended by Ohio EPA. This process manual outlines the procedures necessary to delineate source water protection areas for public water system using ground water.

### 1.1 Definition

A drinking water source protection area is the area that supplies water to a public water supply well within a five-year time-of-travel. This means that a drop of water placed at the edge of the protection area would take five years to reach the well. Ohio EPA also delineates an inner management area (based on a one year time of travel) to help identify the most critical portion of the protection area.

### 1.2 Summary of Delineation Process

**1.2.1 Data Evaluation.** The first step in delineating a protection area is analyzing the information available for the aquifer and site-specific area. Aquifer maps, ground water resource maps, potentiometric surface maps, ground water pollution potential (DRASTIC) maps, and any additional information that is in a Geographic Information System (GIS) coverage or readily available should be analyzed.

**1.2.2 Delineate Protection Area.** Ohio EPA will select a method to delineate each protection area based on three factors: hydrogeologic setting, availability of data, and, in some cases, the amount of water the public water system uses each day. Section 2.0 discusses the methods that will be utilized for SWAP delineations. Section 3.0 provides guidelines for selecting an appropriate delineation method. In general, simple methods should be used for simple settings, and more complex methods should be used for more complex settings. Special situations, such as well interference issues and conjunctive delineations, are discussed in Section 4.0. This methodology reflects an effort to provide the best delineation possible for each public water system.

**1.2.3 Combined Systems and Conjunctive Delineations.** Coordination with the Division of Surface Water is necessary when delineating the SWAP area for public water systems that utilize both ground water and surface water. In addition, a watershed delineation will be completed for systems using ground water that are under the influence of surface water (See Section 4.2).

**1.2.4 Data Management.** Once the delineation is complete, it will be added to the statewide GIS delineation database and attributes used to create the delineation will be recorded.

## 2.0 DELINEATION METHODS

Several different methods will be used to delineate source water protection areas. These methods include shapes based upon the volumetric equation, analytic element modeling methods, and numerical modeling methods.

### 2.1 VOLUMETRIC SHAPE METHODS

Ohio EPA's shape methods for delineating protection areas are based in part on the volumetric equation which requires an understanding of the pumping rate of the wells, the open interval or length of the well screen, and the aquifer porosity. The shape methods do not incorporate parameters such as aquifer hydraulic conductivity or transmissivity, recharge, hydraulic gradient, or hydrogeologic boundaries, all of which could alter the size and shape of the well field's zone of contribution.

**2.1.1 Circle.** The circular shape method delineates a circular protection area using the calculated fixed radius volumetric equation:

$$R = \sqrt{\frac{Qt}{nh\pi}}$$

Where:

R = radius of the circle (feet),
Q = the pumping rate of the well (ft.$^3$/year),
t = the time of travel for which volume is being calculated (years),
n = the porosity, and
h = the length of the well screen (feet).

The applicability of the circle method is limited because in some hydrogeologic settings it may over-protect down-gradient areas as well as under-protect up-gradient areas within the well field's zone of contribution.

**2.1.2 Half-Circle.** Ohio EPA's half-circle method incorporates flow direction by allowing the shape, but not the area, of the calculated circle to be altered. This corrects for some of the limitations of the circle method. If the direction of ground water flow is known within 180 degrees, the half-circle method will allow a circular shape to be altered to a half circle shape oriented in the up-gradient direction of ground water flow. This shape method will more appropriately represent the well field's zone of contribution for areas where the water table is sloped. The equation for a half-circle is:

$$R = \sqrt{\frac{2Qt}{nh\pi}}$$

Where:

R = radius of the circle (feet),
Q = the pumping rate of the well ($ft.^3$/year),
t = the time of travel for which volume is being calculated (years),
n = the porosity, and
h = the length of the well screen (feet).

The application of the half-circle method is illustrated in Figure 1, where a public water system's well is located just north of a river that is flowing west. The hydrogeologist might assume that the primary flow direction in the aquifer is most likely toward the west, following the gradient of the stream. This assumption does not account for other influences on flow direction, such as a potential northerly/northwesterly flow toward the river from an upland area or a southerly flow component produced by pumping-induced flow from the river. Because the flow directions may vary, the hydrogeologist may decide to calculate the volumetric equation for a half-circle, and place the half-circle east of the well. This area covers southerly, northerly and westerly flow to the well. It also covers more of the presumably up-gradient area than the circle would have covered.

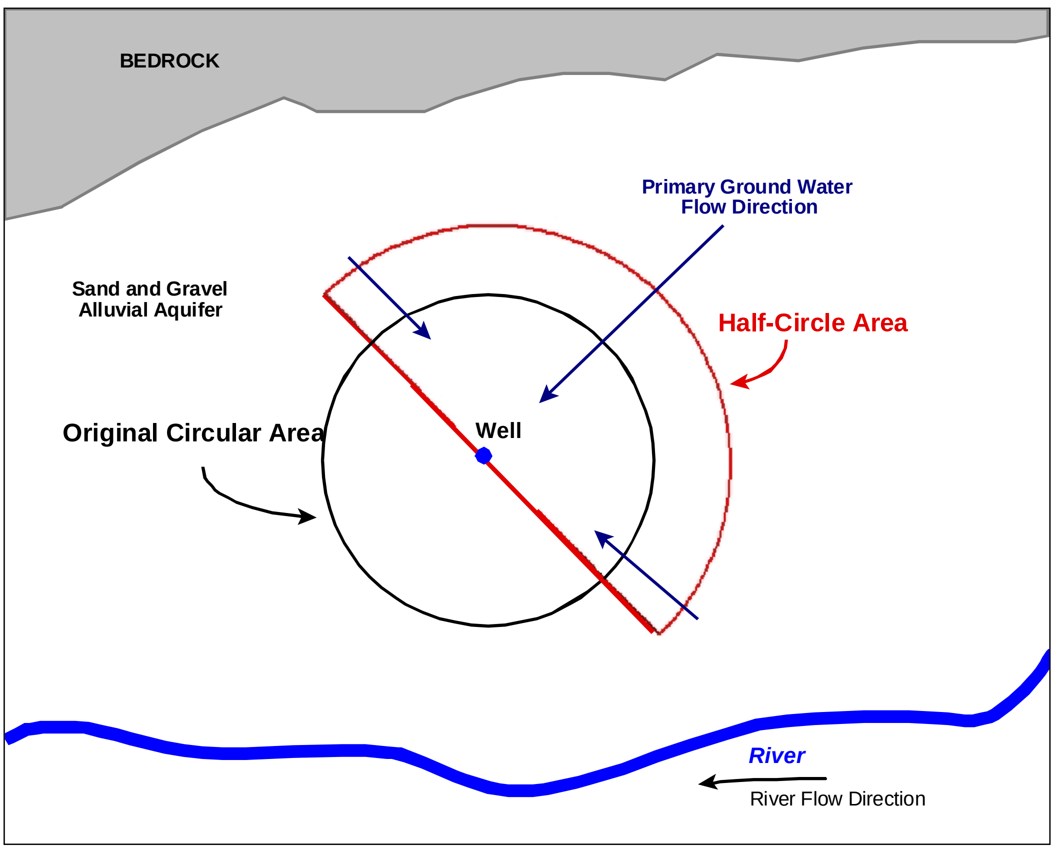



**Figure 1.** Delineating the up-gradient portion of a protection area using the half-circle method (blue arrows indicate possible ground water flow direction).

At this point, the down-gradient side of the well remains unprotected. To provide a down-gradient SWAP area boundary, a small circle is delineated around the well. Lines are drawn tangentially from the smaller circle to the up-gradient volumetric shape, as shown in Figure 2, to create the down-gradient SWAP area boundaries.

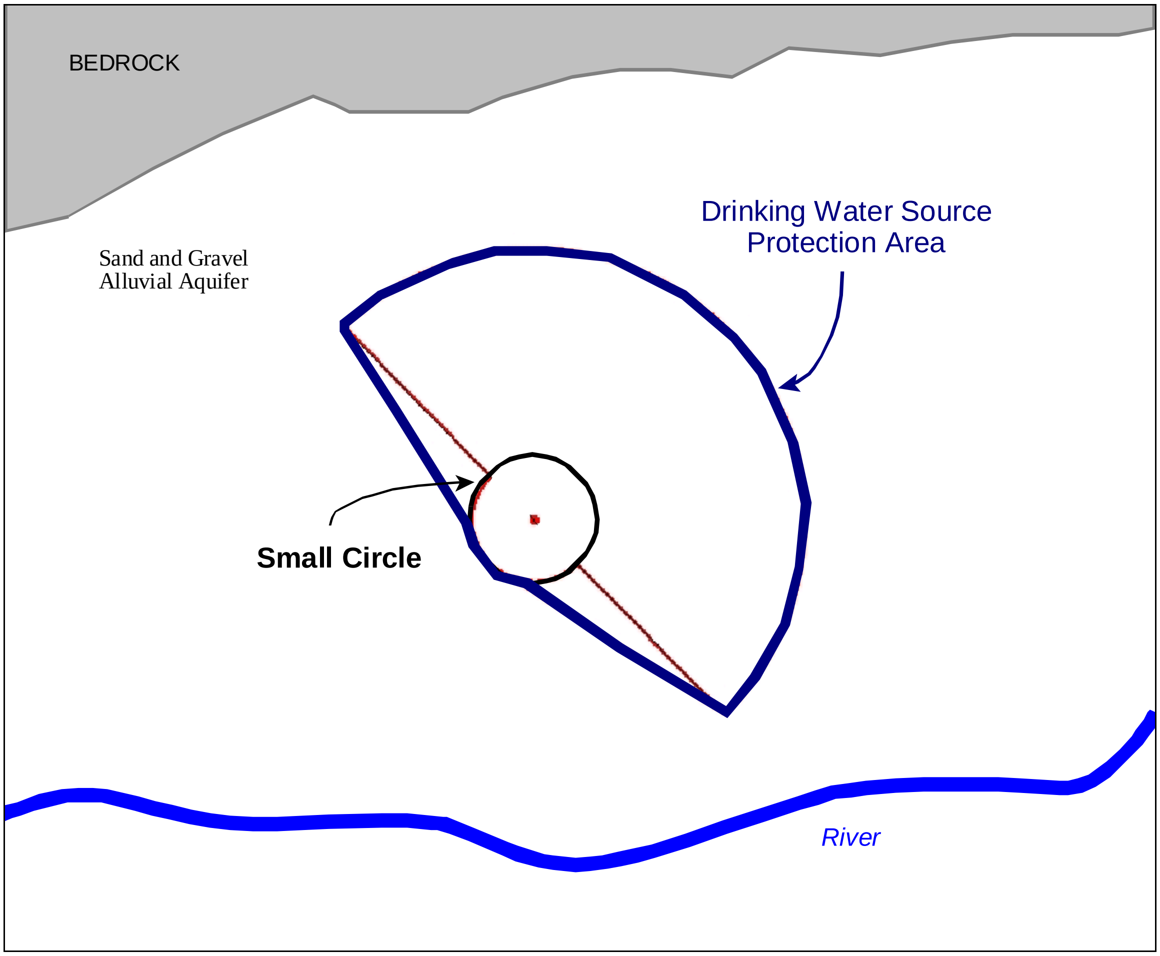



**Figure 2.** Delineating down-gradient potion of the protection area using the volumetric half-circle method.

The radius of the small circle depends on the public water system's pump rate, as follows:

- IF Pump Rate is 2,500 gallons per day (gpd) or less = 50 ft. radius
- IF Pump Rate is 2,500 gpd to 10,000 gpd = 100 ft. radius
- IF Pump Rate is 10,001 to 50,000 gpd, R= 50 + Q/200 (where Q = pump rate)
- IF Pump Rate is 50,000 to 1 million gpd, R= (0.000737)Q + 263.

*The designation of specific down-gradient boundaries is based on modeling that was conducted using the U.S. EPA software MONTEC, and based on Ohio EPA sanitary isolation radii. MONTEC uses a Monte Carlo probability analysis to estimate protection areas for a single well based on a range of possible values for various hydrogeologic parameters. It then delineates protection areas that represent some (requested) percentile of the possible protection areas, given that combination of values. Ohio EPA used the 95 percentile to determine the extent of the down-gradient protection area. For public water systems pumping less than 50,000 gallons/day, the estimated down-gradient extent was very small and the sanitary isolation standard was used as a more conservative value.*

For systems pumping more than 1 million gpd, the SWAP area will be approaching a circular shape but other factors, such as induced recharge from a river and the presence of flow boundaries, may affect the shape of the protection area. For public water systems pumping large amounts of water it is advisable to use a more complex delineation method.

**2.1.3 Half-Circle Modification.** If flow direction is known within 90 degrees the half-circle method can be modified so the arc of the ½ circle is oriented in the up-gradient direction instead of the down-gradient direction. This produces a protection area that protects a greater percentage of area in the up-gradient direction. This method produces protection areas that more closely resemble protection areas derived using the uniform flow equation.

## 2.2 Analytic Element Models

Analytic element models (AEM) are more sophisticated than the shape methods, in that hydrogeologic features such as streams, lakes and flow boundaries can be in incorporated into the model. These models are not based upon the development of a model grid, and therefore, can be developed in less time than more complex, three-dimensional numerical ground water flow models such as MODFLOW. To use an analytical model, ground water flow direction, transmissivity, aquifer thickness, recharge, and porosity must be known or reasonably estimated. Since analytical models assume two dimensional horizontal flow, they may not be appropriate for the prediction of detailed flow patterns and water table head values very close to rivers (local 3-D effects), in karst systems (conduit flow), and for wells that pump very little water (capture zone is very small) (Haitjema, 1995).

Analytic element models can simulate fully penetrating streams and appropriately model unconfined and semi-confined settings. Analytic element models can also be used to simulate simple confined settings using a "box method" similar to creating a sandbox model in MODFLOW (see Appendix C). Their ability to simulate non-rectilinear flow boundaries makes analytic element models appropriate for modeling confined buried valley settings. Ohio EPA will be utilizing two analytical element modeling programs: GFLOW and WhAEM. Appendix C describes how to set up WhAEM and GFLOW models and presents rules of thumb for using GFLOW.

**2.2.1 WhAEM.** WhAEM, a U.S. EPA ground water modeling program, is a two dimensional single layer model that assumes horizontal and steady-state flow and pumping, as well as homogeneous and isotropic aquifer conditions. Mathematical functions are used within the WhAEM model calculations to represent the influences of hydrogeologic features such as streams, lakes, and flow boundaries in order to determine the size and shape of the well field's protection area. If the difference in hydraulic conductivity between two hydrogeologic settings is greater then two orders of magnitude, then the boundary between the hydrogeologic settings can be considered a no-flow boundary. WhAEM can not adequately represent variations in aquifer thickness, hydraulic conductivity, porosity or recharge and WhAEM should not be used if inhomogeneities influence the ground water flow regime. WhAEM also has an option to use the uniform flow equation to calculate protection areas in very simplified settings.

**2.2.2 GFLOW.** GFLOW is a single layer model that assumes horizontal and steady-state ground water flow and pumping conditions in a heterogeneous geologic setting. Mathematical functions are used within GFLOW to represent hydrogeologic features such as streams, lakes, no-flow boundaries, and inhomogeneities. GFLOW can therefore adequately model settings such as buried valleys with permeable sandstone valley walls. GFLOW offers some capabilities for modeling local transient and three-dimensional ground water flow, but is more appropriately used to model regional horizontal ground water flow. GFLOW should be chosen over WhAEM when there are local inhomogenieties that influence the ground water flow regime. GFLOW also has an option to use the uniform flow equation to calculate protection areas in very simplified settings.

### 2.3 MODFLOW MODELS

MODFLOW is a grid based numerical model that provides for multi-layer (multiple aquifer) three dimensional representation of ground water flow (McDonald and Harbaugh, 1984). Aquifer conditions can be defined as either homogeneous or heterogenous, steady-state or transient pumping conditions, confined, unconfined or semi-confined. Ground water flow models such as MODFLOW provide the best solution to understanding both horizontal and vertical flow conditions within an area of interest.

The development of a MODFLOW model to determine a well field's protection area is most appropriate when 1) confident, detailed hydrogeologic data is available for the area, and 2) the complexity of the hydrogeologic setting cannot be appropriately modeled by simpler non-grid based models (Ohio EPA, 1994). The benefits of MODFLOW are that specific details on all hydrogeologic parameters can be represented on a three-dimensional basis within the model to provide both a regional and local scale understanding of the ground water flow and the well field's zone of contribution. The main disadvantage to using a grid based model is the large amount of time and data needed to properly develop and execute the model.

## 3.0 DETERMINING WHICH MODEL TO USE

The method selected to delineate a protection area is based on three factors: the availability of data (potentiometric surface maps, pump tests, etc.), the hydrogeologic setting (carbonate aquifer, sand and gravel aquifer, etc.), and in some cases the amount of water the public water system pumps each day. Ohio's approach does not vary by type of public water system. In addition, arbitrary fixed radii, such as a 500 foot circle, are not used. For all delineations an attempt is made to use site specific data and provide the most accurate source water protection area possible, regardless of the type of PWS.

The flowchart shown in Figure 3 outlines the general methodology used to determine which model will be applied to delineate source water protection areas.

- The flow chart should not be regarded as a rigid set of rules. In general, **analytic element models** (GFLOW and WhAEM) and numerical models (MODFLOW) should be used for complex hydrogeologic settings, such as coarse grained sediment aquifers.
- In simpler confined or semi-confined settings the **box method optio**n in WhAEM (or GFLOW) should be used, if data is available for the area.
- The **shape method** should be limited to systems in:
    - carbonate aquifers that pump less than 10,000 gallons per day;
    - other aquifers that pump less than 25,000 gallons per day; or
    - areas that lack the data necessary to develop an analytic element model.

The following sections describe the rationale behind delineation method selection in more detail.

### 3.1 Availability of Data

The choice of a delineation method, in an ideal world, is governed by a simple rule: simple methods for simple hydrogeologic settings; sophisticated methods for complex hydrogeologic settings. In reality, data availability is the limiting factor in method selection. Simple methods need a minimum of data while sophisticated methods are almost useless without abundant data of reasonably high quality. Since abundant high quality data are rarely in supply and are prohibitively expensive to acquire, hydrogeologists are often left with no choice but to apply simple methods to complex settings.

Ohio's available GIS layers will provide much of the data necessary to delineate protection areas. However, availability of potentiometric surface maps is critical for delineation method selection. A regional potentiometric surface map for Ohio's western carbonate aquifers was completed by the United Stated Geological Survey. Additional county scale maps have been completed by USGS and the Ohio Department of Natural Resources Division of Water for several Ohio counties. If a potentiometric surface map is not available for an area, Ohio EPA staff may develop a local potentiometric map using historic well logs. Where insufficient well logs exist to create a potentiometric map, other methods of estimating a flow direction and gradient may be undertaken. If data are lacking for even a flow direction estimate, hydrogeologists will have no choice but to use some variation of the volumetric equation.

### 3.2 Hydrogeologic Setting

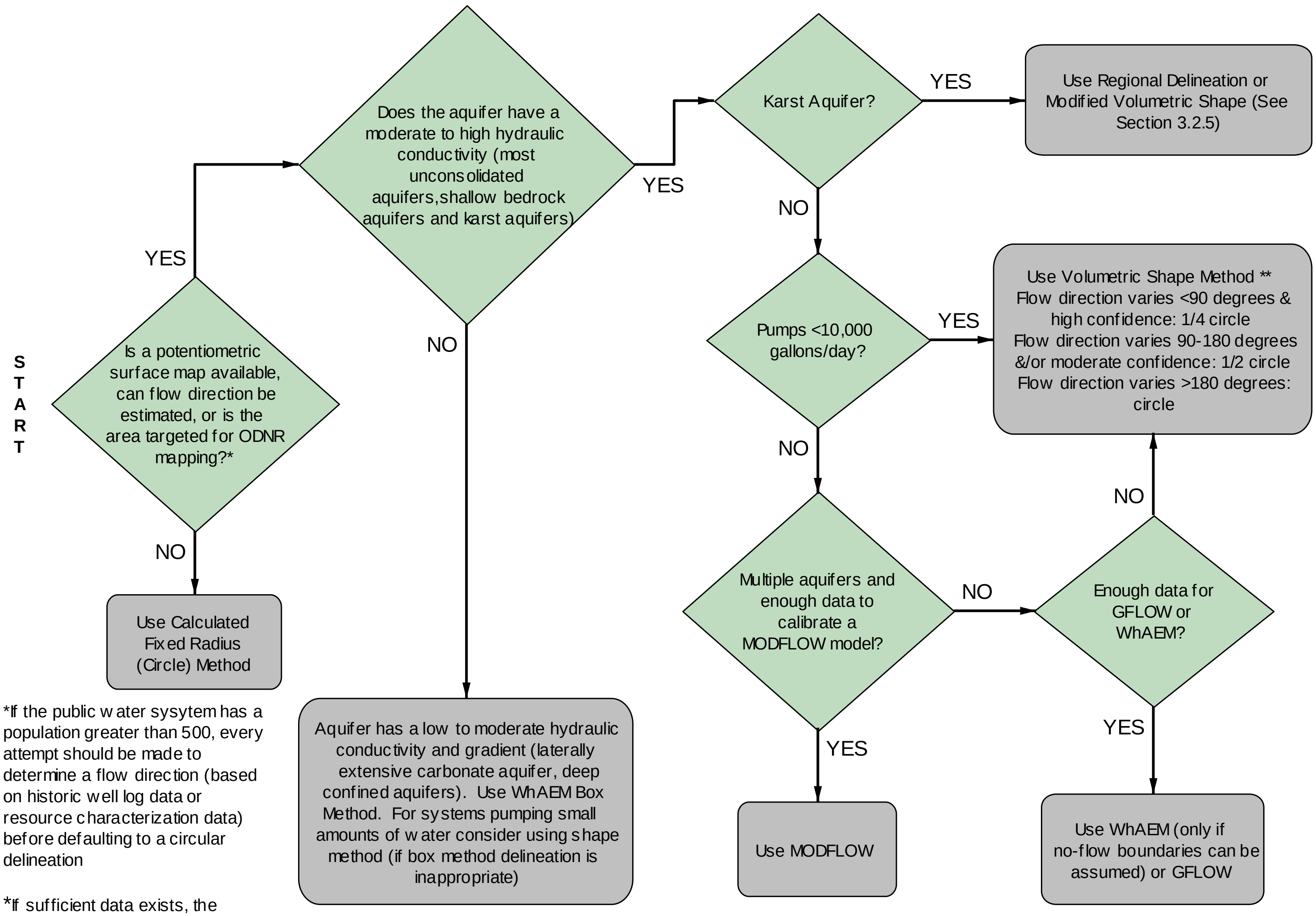
The delineation method selection varies based on hydrogeologic setting because average linear velocity differs for different hydrogeologic settings. The average linear velocity, which takes into account hydraulic conductivity, gradient, and porosity, dictates the shape of a protection area (Ohio EPA, 1994). In hydrogeologic settings with low average linear velocities (primarily low hydraulic conductivity and gradient values), protection areas are more circular and simplistic delineation methods can be applied. In settings with higher average linear velocities, protection areas are longer and narrower, and more complex delineation methods may be required.

**3.2.1 Coarse Grained Sediment Aquifers.** Coarse grained sediment aquifers are characterized by relatively homogeneous coarse-grained sediments with moderate to high hydraulic conductivity and a moderate to high average linear velocity (Fetter, 1991; Freeze and Cherry, 1979; Driscoll, 1989). These aquifers include buried valleys, alluvial settings, valley fill, beach ridges, and outwash/kame deposits. Coarse-grained sediment aquifers often have complex flow boundaries in the form of valley walls (usually barrier boundaries) and streams (recharge boundaries). Typically the streams penetrate the aquifer only partially, and may or may not be in hydraulic connection with the aquifer. In addition, a public water system may have wells drilled into both a shallow unconfined aquifer and also a deeper confined aquifer. In these types of complex settings a more complex model, such as GFLOW, is preferred.

Ohio EPA staff will consider using the numerical ground water flow model MODFLOW, with the particle tracker MODPATH, to delineate systems located in more complex settings (such as multiple aquifer settings) provided there are an acceptable quantity and quality of water level data with which to calibrate the model. The MODFLOW modeling will be done for an entire aquifer or section of an aquifer rather than for a single public water system. MODFLOW-delineated SWAP areas will be primarily for community systems. Non-community systems that pump a significant amount of water may be delineated with this method, but it is assumed that these will be exception rather than the rule.

In some cases, more complex analytic element models and numerical models may not produce appropriate delineated protection areas. This is especially true for public water systems that are intermittent pumpers and pump small amounts (less than 10,000 gallons/day) of water. This issue is discussed in more detail in Section 3.3.

**Figure 3. Delineation Method Selection Flowchart**




*If the public water sysytem has a population greater than 500, every attempt should be made to determine a flow direction (based on historic well log data or resource characterization data) before defaulting to a circular delineation

*If sufficient data exists, the modeler may choose to use GFLOW or WhAEM, as long as the area determined by the model is reasonable.

**3.2.2 Non-karst Carbonate Aquifers and Deep Confined Bedrock Aquifers.** Non-karst carbonate aquifers and deep confined bedrock aquifers in Ohio are characterized by relatively low hydraulic conductivity values and low to moderate gradients (Hanover, 1994). Aquifers in this category include the laterally extensive carbonate aquifers in western Ohio, deep bedrock aquifers (gradient is controlled by shallow dip of bedrock, not topography), and till plains. The combination of low hydraulic conductivity and low to moderate gradient has a profound effect on the shape of the five-year capture zone. Where both hydraulic conductivity and gradient are low, the capture zone will be nearly circular, even at very low rates of pumping. Generally, systems pumping small amounts will generate more circular capture zones in this setting than a system pumping the same amount in a coarse-grained aquifer setting. This means that in these settings it may be more reasonable to delineate protection areas using an analytic element method or the uniform flow equation if flow directions are known (even for small pumpers), or a volumetric circle if information on flow direction is lacking. Volumetric shapes should be limited to areas where the pump rate is very low and produces inappropriate shaped protection areas (See Section 3.3).

A generalized potentiometric map that covers a large portion of a regional carbonate aquifer in western Ohio was completed by the United States Geological Survey in 1994. The map was based on water levels measured concurrently in selected wells throughout the region. Modelers should delineate most of systems in this carbonate setting with WhAEM/GFLOW, using the USGS potentiometric map to determine flow direction(s) and gradient.

**3.2.3 Sandstone, Shale, and Interbedded Shallow Bedrock Aquifers.** The guidelines for coarse-grained sediment aquifers apply in large part to bedrock aquifers with high gradients. This is because when the gradient for bedrock aquifers approaches 0.01 or greater, the resulting protection area is shaped more like the area of a coarse-grained aquifer. Bedrock aquifers that exhibit high gradients are typically shallow (located above the floor of the nearest major valley), and are located in areas with significant topographic relief. It is expected that topography will provide the best indicator of flow direction for many systems in this setting. The determination of flow direction is most reliable where the well is shallow, drilled into an unconfined to partially confined aquifer, and the screened or open area is located topographically higher than the nearest valley.

If flow direction information is available then GFLOW or WhAEM can be used. However, the volumetric shape method will be used for delineating most of the systems within this setting, largely because these aquifers generally do not exhibit the complex flow boundaries and these settings tend to have very little information available about them. With the exception of northeast Ohio, where the Sharon Conglomerate and other hard-rock aquifers are used by numerous community water systems, the majority of public water systems using this kind of aquifer are small systems. The owners and operators of smaller systems are least likely to have detailed information about the aquifer.

**3.2.4 Karst**. In an attempt to identify potential karst regions, Ohio EPA digitized the locations of surficial karst features and created a map (based on ODNR aquifer GIS data) of carbonate aquifers that have less than 25 feet of glacial cover and are prone to developing karst (Figure 4). In 2001, the U.S. EPA Region V Karst Workgroup discussed the influence of glacial cover on karst development and determined that karst could likely form with a maximum of 25 to 50 feet of glacial cover. The Ohio Department of Natural Resources, Geological Survey, had previously determined that surficial karst features were not identified if greater than 25 feet of glacial deposits were covering the carbonate aquifer. Since 25 feet is Ohio EPA's current well depth standard and a

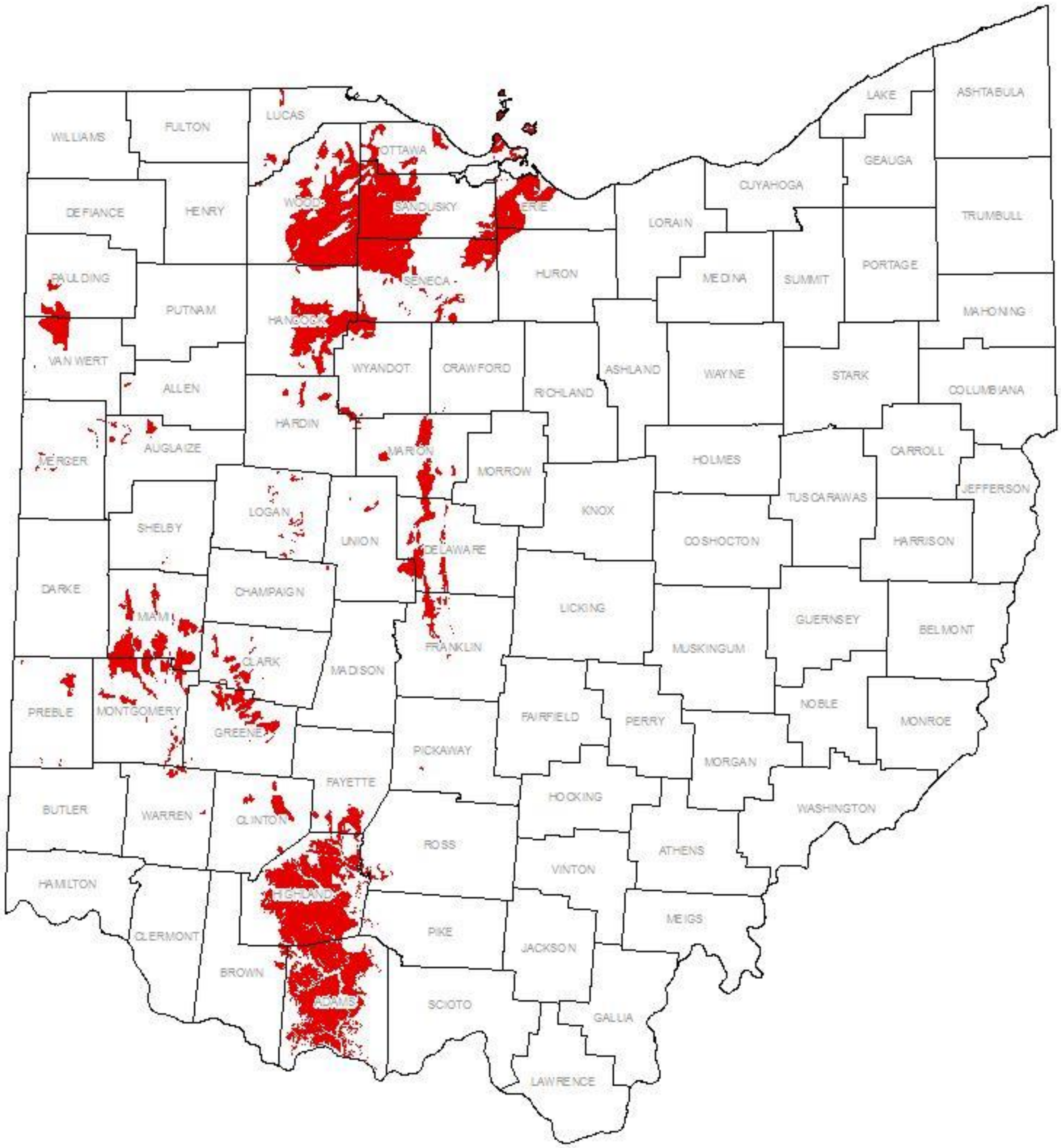



**Figure 4.** Areas of potential karst geology.

statewide map of areas with less than 25 feet of glacial cover existed, Ohio EPA decided to use 25 feet as the cutoff for potential karst regions.  In addition, the potential karst region excludes select dolomite aquifers that do not exhibit surficial karst features and Ordovician aged carbonates.  The Ohio Department of Natural resources confirmed that the excluded dolomite aquifers were unlikely karst aquifers.  The dolomite aquifers that were excluded are still relatively susceptible to contamination, but since surficial karst features were not found in these regions it was assumed that large solution channels were not formed and the flow rates were more analogous to a typical fractured bedrock aquifer. Therefore, the excluded thin till dolomite aquifers will be delineated using the non-karst carbonate aquifer methodology (Section 3.2.2).  The Ordovician carbonates were excluded because no public water system wells used the Ordovician carbonates as a source of water (due to the presence of the highly productive sole source buried valley aquifers that are incised into the Ordovician carbonates).

In addition, not all of the public water systems in the potential karst areas were identified as karst and additional public water systems that are outside the potential karst were identified as karst.  For example, if a public water system was located in a shallow alluvial valley that overlay the potential karst area it was not be considered karst and was delineated based on the coarse grained sediment aquifer guidelines.  In addition, when conducting assessments for public water systems that are near the potential karst region (within 2 mile) staff checked the depth to bedrock on the public water system's well log.  If the well log indicated the public water system has less than 25 feet depth to limestone bedrock, it was treated as a potential karst setting (even though it is out of the mapped potential karst region).

**3.2.4.1 Initial Karst Delineation Methodology.** From 2001 until January 2007 Ohio public water systems located in karst areas were delineated using a variation of the calculated fixed radius equation.  Site-specific pumping information was used, but default values of 1% porosity and ten feet aquifer thickness (or less if the open borehole thickness was less than 10 feet) were used in the equation.  The porosity value was lowered from the standard value of 3% for carbonate aquifers to provide for a more conservative delineation, given the uncertainty of hydrogeologic information in karst settings.  This simplistic delineation method was chosen primarily due to a lack of time to collect additional data on the karst aquifers or conduct dye traces or detailed fracture flow modeling for hundreds of water systems located in karst settings.

The primary issue with the delineation method used in karst regions is the protection areas for the municipal community public water systems can be extremely large, and may be overprotective in the down-gradient direction and potentially under-protective in the up-gradient direction.  Since many Ohio rules and regulations are being tied to drinking water source protection areas, these areas are coming under increased scrutiny. The large source water protection areas created using the default karst region delineation method are not readily scientifically defensible.  While Ohio EPA's potential karst approach was consistent, the selection of 10 feet as an aquifer thickness and 1% porosity was not backed by site-specific data.

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**3.2.4.2 Karst Redelineation Workgroup and Revised Karst Areas.** In 2006 a karst redelineation protocol was developed to address the need for more scientifically defensible drinking water source protection areas for the 167 public water systems located in karst areas and delineated using the initial karst delineation method. The protocol was developed by an internal Ohio EPA workgroup, consisting of Heather Raymond (CO), John McGinnis (SWDO), Pat Heider (NWDO), Mike Bondoc (CDO), Linda Slattery (CO), Barb Lubberger (CO), and Mike Eggert (CO; Team Sponsor).

The karst workgroup evaluated whether or not the criteria that were used to classify a public water system as karst were appropriate. The workgroup decided that the 25 feet till thickness cutoff should not be reduced after researching other state karst criteria and learning that several other states define areas with even a thicker till layer as karst and no states used a thinner till thickness cutoff. However, the karst workgroup felt that there might be special circumstances where an individual well should be excluded from the karst definition and delineated using a traditional method. The karst workgroup developed the following list of criteria for <u>excluding</u> PWSs from a karst classification:

1. 25 feet depth to bedrock.
2. Clear evidence that the well(s) is confined.
3. Best Professional Judgment, based on factors such as:
    a. Low D.O. (<1.0 mg/l). If this information is not available for a municipal community PWS, the district staff may collect it prior to redelineating the water system using the revised karst delineation method.
    b. Lithology (tight formation, absence of secondary porosity features, more dolomitic aquifer, etc.).
    c. Lack of surficial karst features (sinkholes, losing streams, springs, caves, etc.).
    d. 20-25 feet depth to bedrock (near 25 feet cutoff combined with other factors).
    e. Lack of water quality impacts (nitrate, etc.), especially for wells <50 deep.
    f. Negative Oxidation Reduction Potential (ORP).

District staff with expertise in the local geologic setting may determine what combination of the above-mentioned factors would be necessary to exclude a water system from the karst classification.

Staff can also use the following list of indicators for karst formation, developed by the Minnesota Department of Health, as rationale for <u>including</u> a public water system located in a carbonate aquifer within the karst classification:

1. Indicators of rapid surface water recharge to the well:
    a. Well water becomes turbid following rainfall or snowmelt.
    b. Well water shows bacterial contamination following rainfall or snowmelt.
    c. Chemical or isotopic analysis or temperature changes of the well water indicate surface water mixing with groundwater.
    d. Water can be heard running into the uncased portions of the well.
    e. Air is sucked into the well or blown out as barometric pressure changes.
    f. Rapid increase in the static water level.
2. Indicators of secondary porosity features at the well site:
    a. The driller’s log indicates cavities or large fractures were encountered during drilling
    b. Video logging shows the presence of fractures or cavities.
    c. Presence of cavities indicated by caliper, acoustic, sonic, or other borehole geophysical instruments.

d. Pumping test analysis indicates that water level response to stressed conditions is being influenced by recharge from secondary porosity features.
e. Cuttings samples could not be collected because of voids that were encountered at these intervals.
f. Evidence of rapid horizontal flow such as grout migrating from new well construction to existing wells or springs.

3. Regional indicators of secondary porosity features in the bedrock:
   a. The bedrock topography exhibits linear features such as ridges and valleys that abruptly change orientation or terminate abruptly.
   b. Exposures of the bedrock show fracturing, structural deformation, or solution-weathered features.
   c. Rock cores of the bedrock show fractures or solution-weathered features.
   d. Karst features, particularly sinkholes and disappearing streams, or the lack of surface water bodies, indicate rapid recharge to the bedrock is occurring.
   e. Mapping shows the bedrock aquifer is part of a springshed, or springs are present that drain carbonate rocks.
   f. Tracer studies show pathways from secondary porosity features to the well.
   g. The migration of contaminant plumes in the bedrock indicate preferential flow along linear features such as faults or fracture directions.
   h. The entire region up-gradient of the well has less than 25 feet depth to bedrock and exhibits one or more of the secondary porosity features mentioned above.

**3.2.4.3 Karst Redelineation Method.** The following redelineation method is proposed for all public water systems located in potential karst areas, regardless of system size or pump rate. The method is based in part on an approach used by the Minnesota Department of Health, and incorporates elements of hydrogeologic mapping and volumetric determinations.

**Step 1.** Determine a five-year calculated fixed radius using the volumetric equation (see section 2.1.1). Unlike the initial karst delineations, aquifer thickness will be based on the actual aquifer thickness at the well location (see section 5.1.3) and porosity will default to 3%, unless site-specific porosity data is available for the aquifer.

The **calculated fixed radius** area determined in step 1 will be considered the **inner management zone** for public water systems in karst areas. The outer management zone is calculated in Steps 2-7.

**Multiple Wells.** If there are multiple wells in a karst area and the protection areas overlap, a regional composite protection area may be appropriate. If the inner management zones determined in Step 1 overlap, the Ohio EPA ArcView Shape Method application can be used to address potential well interference issues and ensure a large enough circular area is delineated in Step 1.

**Step 2.** Extend the calculated fixed radius (determined in Step 1) up-gradient to one of the following boundary conditions (in decreasing order of preference):

A. Geologic boundary, such as a different bedrock unit;
B. Groundwater flow divide;
C. Extensive surface water feature that is hydraulically connected with the aquifer, including surface water features that follow cross-cutting fractures. Examples include

perennial rivers, streams, or lakes, whose volume is at least comparable to the volume calculated in Step 1.

**Step 3.** If there is uncertainty in flow direction or the flow direction fluctuates, the area should be expanded laterally to address the variation in flow direction and uncertainty.

**Step 4.** The effects the orientations of fractures have on the contribution area to the well should be addressed if the primary flow direction differs from the primary fracture orientation, fracture traces are apparent at the ground surface, fractures are widely spaced and do not form an interconnected fracture network, and fracture data is readily available. The contribution area(s) attributed to fractures should be determined by orienting the capture zone determined in Step 1 along the compass orientation of fractures. Extend the capture zone obtained in Step 1 up-gradient along the compass orientation of a fracture until one of the following boundaries is encountered (in decreasing order of precedence): A) a geologic boundary, such as a different bedrock unit; B) a groundwater flow divide; C) an extensive surface water feature that is hydraulically connected with the aquifer; or D) the five-year time of travel extent determined using the Darcy equation.

**Step 5.** Prepare a composite capture zone. Merge the areas generated from Steps 1, 2, 3, and 4 to define the drinking water source protection area.

**Step 6.** In rare circumstances it may be appropriate to expand the protection area to include areas where surface water runoff may enter the protection area and quickly recharge the aquifer through infiltration or direct discharge into karst features such as sinkholes, disappearing streams, or exposed bedrock. If karst features occur within the protection area determined in Step #5, the springshed or watershed that drains such features should be added to the protection area. In addition, areas of higher topography that are adjacent to the protection area determined in Step #5 should be included if surface drainage from them may reach geologically sensitive portions of the aquifer. Before the delineation is expanded based on items outlined in Step 6, the district staff person should discuss the expansion of the area with the karst workgroup. This will ensure consistency of application of step 6 throughout the three district offices and central office.

**Step 7.** Merge the boundaries of the surface water contribution area(s) determined in Step 6 with the composite capture zone that was prepared in Step 5. The combined area obtained from Steps 5 and 6 forms the drinking water source protection area.

**Step 8.** Update the statewide delineation shapefile with the new delineation and revised input parameters.

**3.2.4.4 New Public Water Systems in Karst Areas & Karst Reevaluations.** All new public water system wells that are drilled in a karst area will be delineated using the revised method outlined above. In addition, once the existing karst delineations have been revised using the new method, staff will evaluate whether or not other public water systems located outside the original karst area should be redelineated using the new karst delineation method. This evaluation is important because during field investigations staff found errors in the statewide glacial aquifer map that Ohio EPA originally used to determine till thickness. For example, staff observed bedrock at the ground surface in areas mapped as having >25 feet of till. In addition, some of the karst features in our GIS shapefile currently lie outside the less than 25 feet of till area, indicating that either the area was mapped incorrectly or these features can occur in regions with thicker till than originally considered possible. Since new information, such as the bedrock topography DEM and surficial DEM, is now available, staff will compare areas mapped with less than 25 feet of bedrock using the updated data with the thin till areas on the glacial aquifer map. If new thin till areas are found, the water systems within those areas will be evaluated and may be redelineated using the new karst method.

**3.2.5 Isolated, Cavernous Aquifers, Including Old Mines**. Public water systems that utilize old mines as their source of water may be delineated by determining the extent of the mine plus some recharge buffer as the delineated area. If the extent of the mine cannot be determined, the circle shape method will be used. The inner management zone for these public water systems should be determined using the revised karst methodology (see section 3.2.4.3 "Step 1").

### 3.3 Pump Rate

Analytic element models and MODFLOW models often do not provide appropriate delineations for public water systems with small pumping rates that are located in hydrogeologic settings with moderate to high average linear flow velocities. For example, in Figure 6, the public water system in the upper portion of the figure pumps 500,000 gallons per day, and the public water system in the lower portion of the figure pumps 1,000 gallons per day. The hydraulic conductivity in the valley is 300 ft/day. The GFLOW delineated five year time of travel pathlines (protection area) for the water system pumping 1,000 gallons per day is almost as long as the protection area for the larger public water system, but not nearly as wide. The GFLOW delineation for the smaller public water system is inappropriate because most small public water supplies pump intermittently, flow direction may vary seasonally in river valley aquifers, and flow direction information is often imprecise.

**3.3.1 Intermittent Pumping.** Many of Ohio's smallest public water systems pump intermittently. This means the water system does not pump at a continuous rate throughout the day. Instead, they may pump at a fairly hard rate for a short period of time to fill up a tank, and then stop pumping until the next day. While pumping, the capture area around the well may be fairly extensive, and somewhat circular. Ideally, the SWAP area for such a system would include all the capture area created at the height of pumping and extend up-gradient from that shape in accordance with natural background flow directions and gradients. Unfortunately, analytical element delineation methods are difficult to apply to this scenario because they are not designed to handle intermittent, nonsteady pumping conditions. If the actual pumping rate is input, the model will simulate a well pumping at that rate 24 hours a day, which will produce an inappropriately shaped SWAP area (see Figure 6). If the daily pumping rate is input, the model will simulate a well steadily pumping at a much lower rate, thereby underestimating the actual area contributing to the well when the pump is on, and potentially overestimating the up-gradient reach of the SWAP area.

Numerical methods are best equipped to simulate SWAP areas for transient pumping scenarios, but from the standpoint of resources, it would be impossible to create numerical models for each of Ohio's 4,000 transient systems and often data is lacking to create a numerical model. Many small systems do not maintain flow meters, and may not know how often the pump cycles on and off. Most systems provide their pumping information in terms of gallons per day and, in many cases, this number is an estimate based on the average number of people who use the water each day and rules of thumb regarding the average amount of water each of those individuals would use. It is worth noting that a system pumping 10,000 gallons/day is pumping an average of 7 gallons/minute, and few systems located in aquifers with moderate to high hydraulic conductivity values would be expected to have a pump set at this rate. Rather, the system would have installed a higher rated pump (e.g., 30 gallons/minute) that pumps to a water tank until it is full, then shuts off. Based on this reasoning, Ohio EPA will assume that any system that is pumping 10,000 gallons/day (gpd) or less is pumping intermittently.

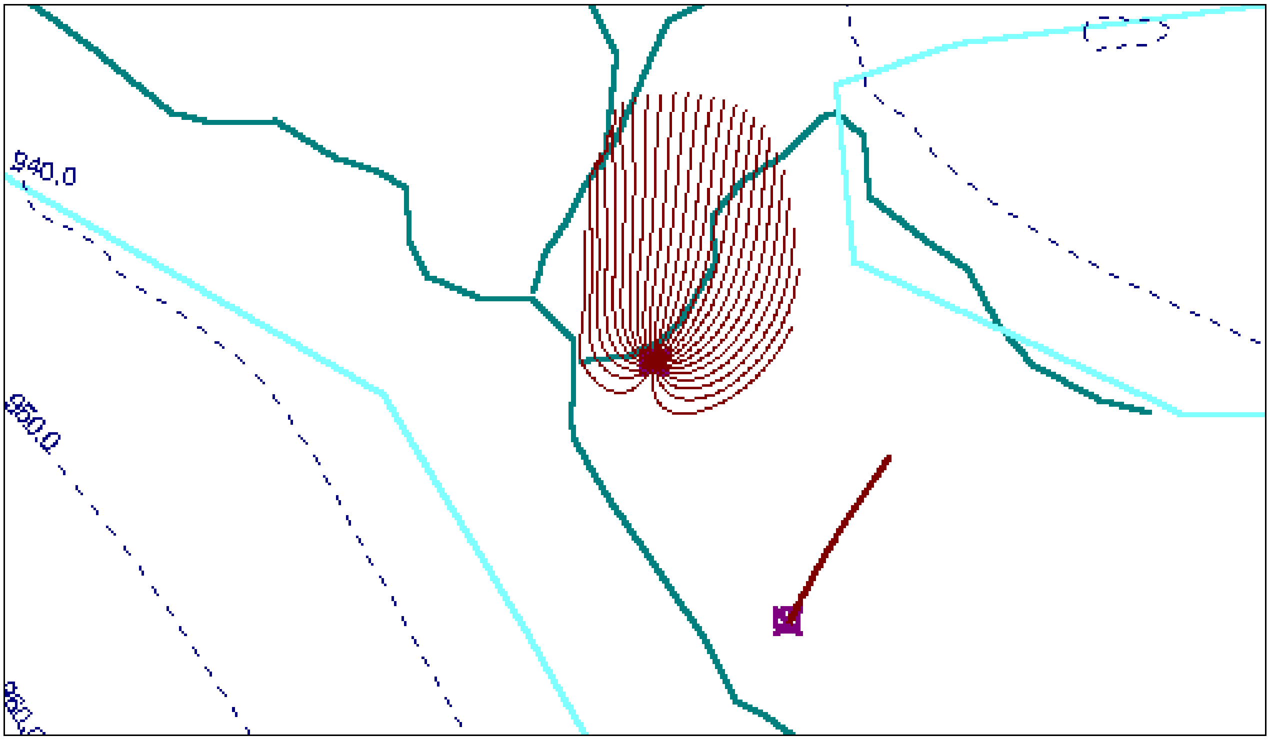


**Figure 5.** Protection areas delineated using GFLOW for water systems pumping 500,000 gallons/day and 1,000 gallons/day.

**3.3.2 Seasonal Variation in Flow Direction.** Analytical element models may be inappropriate for small pumping water systems located in unconfined alluvial settings because the flow direction may vary seasonally. Shifts in flow direction are due to fluctuations in river stage. When the river stage is low, the river behaves as a gaining stream and flow direction is typically towards the river. In the spring, when river stage is high, flow direction may reverse and flow away from the river. The long and narrow protection areas delineated using analytic element models assume a single flow direction and provide little protection for the down gradient area around the well(s).

**3.3.3 Lack of Precision in Flow Direction Data.** The narrow protection area produced by analytic element models (for small pumpers) requires an accuracy in flow direction information that is difficult, if not impossible, to have. The protection area delineated by analytic element modeling may not include the actual five year time of travel area and is therefore inappropriate.

**3.3.4 Appropriate Delineation Methods.** Public water systems that pump less than 10,000 gallons/day and are located in areas with moderate to high average linear velocities will be delineated using a volumetric shape method, unless the small system is nested within the protection area of another public water system or the shape method delineations for multiple small pumpers overlap (See Section 4.0). If sufficient information exists and the modeler believes the average linear velocity will be low enough to produce an acceptable delineation, WhAEM or GFLOW can also be used. Intermittent pumping will not be assumed for systems pumping greater than 10,000 gallons/day, but if there is documentation indicating that a system's pump is routinely idle for 12 or more hours of a dayBand another well does not cycle on in its placeBthen the system may be handled as an intermittent pumper. This exception applies primarily to small systems, as it is very unlikely that a system pumping several hundred thousand gallons or more per day would fully recover within 12 hours. The half circle method should be used when flow direction varies between 90 and 180 degrees seasonally, or in areas where flow direction information is limited or has to be estimated. The modified half-circle method should be used in areas where flow direction varies less than 90 degrees. The half circle and modified half-circle methods alleviate the problems associated with accuracy of flow direction information and seasonal variation in flow.

# 4.0 SPECIAL SITUATIONS

## 4.1 Combined Public Water Systems

A combined public water system is any public water system that has both a surface water source (intake on stream, reservoir, etc.) and a ground water source (wells). If there are combined systems the district ground water staff person should contact the district Division of Surface Water staff person responsible for surface water assessments and coordinate assessments if possible. Combined public water systems should be made aware that the ground water source water assessment is only part of their complete source water assessment.

## 4.2 Conjunctive Delineations

A conjunctive delineation is a full or partial watershed delineation and inventory completed for a public water system that uses ground water wells. Conjunctive delineations may be appropriate for public water systems with wells that receive a portion of their water through infiltration from a surface water source. This may be the case for water systems designated as "ground water under the influence of surface water" due to infiltration from streams or recharge basins. Central office staff will determine whether or not a conjunctive delineation is necessary on a case by case basis.

## 4.3 Well Interference Issues

The delineation method selection guidelines presented in Section 3.0 may not be adequate for public water systems located in close proximity to each other, due to well interference issues. Analytic element and numeric modeling take into account well interference issues, but the shape method does not. As a result, in areas with multiple public water systems the use of the shape method should be carefully evaluated. Two scenarios will be discussed in this section: nested delineations and overlapping delineations.

**4.3.1 Nested Delineations.** Nested delineations occur when small public water systems are located within the protection area of a larger pumping public water system. If the larger public water system was delineated using GFLOW or WhAEM, the modeler should add the small public water system to the model and evaluate if the small pumper has a significant influence on the shape of the larger pumper's delineation. The modeler should also evaluate whether or not an analytic element delineation is appropriate for the small pumper. If the difference between the small system's pump rate and the large system's pump rate is great (1,000 gallons/day versus 1 million gallons/day production) the interference effects should be negligible and the shape method could be used to delineate the smaller public water system. Modelers should use best professional judgment to determine how to delineate small systems when the difference in pump rates is not as great.

**4.3.2 Overlapping Shape Method Delineations.** In areas with multiple small public water systems in close proximity to each other, shape method delineations may overlap. In these areas, modelers should attempt to use GFLOW or WhAEM (if enough information is available to develop an AEM model) to model the group of small systems together to account for well interference effects. Modelers should use their best professional judgment to determine if the overlapping areas are acceptable, or if an analytic element model provides more appropriate delineations.

# 5.0 DATA ACQUISITION

## 5.1 Delineation Input Parameters

Values for pump rate, aquifer thickness and porosity are necessary for all the modeling methods discussed in Section 2.0. Hydraulic conductivity and recharge may be necessary to complete the delineation if all analytic element or numerical model is used. This section discusses how to determine what model input parameters to use and reasonable values that can be used when data is lacking.

**5.1.1 Pump Rate**. Transient PWS: The pump rate identified in Ohio EPA sanitary surveys should be used if it indicates the rate was estimated. The sanitary survey estimates are very conservative. If the survey indicates the pump rate is the systems actual, meter, pump rate, the hydrogeologist should add 15% to the actual pump rate in an effort to provide a conservative delineation.

Community and Non-Transient Non-Community PWSs: Use the plant capacity from the sanitary survey information if they have a water treatment plant. If the public water system does not have a plant, use 15% more than the average pump rate in an effort to provide a conservative delineation. If the plant capacity is much greater than the average pump rate and the public water system does not expect to expand, the protection area may be delineated using 15% more than the average pump rate.

New Systems and Systems Without Completed Sanitary Surveys: If there is no information on pump rate in the Ohio EPA public water system files and the public water system is unaware of how much it pumps each day, the Drinking Water inspector that deals with the public water system in question should be asked if they can estimate the system's pump rate based on Ohio EPA guidelines. If necessary, the drinking water or ground water staff person should contact the public water system to obtain the facility information required to estimate pump rate.

Standby Wells: If the Public Water System has standby wells they should be modeled using the total pump rate (unless a well is not capable of producing the total pump rate, in which case the well's pump capacity should be used). Standby wells should be included in the model since standby wells would provide water to the public water system in the event that the primary well becomes contaminated.

**5.1.2 Recharge**. For unconfined settings, the low end of recharge identified in the Ground Water Pollution Potential (DRASTIC) coverage should be used (if available). If a DRASTIC map is not available, use information in Resource Characterization database or use Pettyjohn's "Preliminary Estimate of Ground-Water Recharge Rates, Related Streamflow and Water Quality in Ohio" to estimate recharge for the area. If a similar hydrogeologic setting exists in an area with DRASTIC mapping, the modeler can use the recharge indicated for the similar setting.

Use zero recharge for confined settings, or use best professional judgment if data on recharge exists. For semi-confined settings use best professional judgment to determine a value between zero and the actual unconfined recharge. In areas where Tritium data is available, if the water is pre-1953 (below 0.8 Tritium Units) you should not apply recharge to the model. If the water has detectable levels of tritium use best professional judgment to determine if adding recharge to the model is appropriate.

**5.1.3 Aquifer Thickness**. The following table should be used to determine what aquifer thickness value to use for delineating the protection area:

**Table 1.0 Determining Aquifer Thickness for Modeling**

| Aquifer Type | Method to Determine Aquifer Thickness |
|---|---|
| Sand & Gravel (unconfined) | Bottom of the well screen to the water table.* |
| Sand & Gravel (confined) | Bottom of screen to bottom of confining layer; minimum of 5 feet. If the public water system pumps a large amount (1MGD) use best professional judgment to determine if total aquifer thickness should be used. |
| Massive Sandstone | Thickness of saturated sandstone units (if no information about saturation is available, use total thickness of sandstone units) |
| Interbedded bedrock | Thickness of saturated units (Use best professional judgment to determine which units are the main water contributors) |
| Carbonate | Bottom of the open borehole to the water table or bottom of confining layer. |
| Shale | Bottom of the open borehole to the water table or bottom of confining layer. |

**When modeling an unconfined system in WhAEM/GFLOW, the aquifer thickness may need to be thicker to get the model to run because of far field conditions and to ensure the aquifer is behaving as an unconfined aquifer (personal communication, Henk Haitjema). This is acceptable, since the model considers that the top of the water table is the top of the model. First, try the model at the actual aquifer thickness. If the model does not run, increase the aquifer thickness until the model runs. If the aquifer thickness is increased, re-evaluate the resulting potentiometric surface to ensure it is acceptable (make sure the water table near the well field is at an acceptable level and not above the ground surface).*

If the public water system does not have a well log, use the Ohio Department of Natural Resource's online well log database for local logs to determine an appropriate aquifer thickness. If no data exist use the following default values: If Q<50,000gpd = 10ft; If Q>50,000gpd = 25ft. These values are conservative and based on recommendations from the SWAP delineation workgroup.

**5.1.4 Hydraulic Conductivity and Porosity**. If there are no data on hydraulic conductivity or porosity that can be applied to the public water system under consideration, use the following input parameters:

**Table 2.0 Default Values For Delineating SWAP Areas**

| Aquifer Type | Porosity | Hydraulic Conductivity (ft/day) |
|---|---|---|
| Sand & Gravel | .20 | 300 |
| Massive Sandstone<br>(hydrofractured) | .10<br>.15 | 20<br>20 |
| Interbedded bedrock | .15 | 9-15* |
| Carbonate | .03 | 9 |
| Carbonate (karst) | .03 | 500-20,000 (select value based on regional karst dye trace data) |
| Shale | .03 | 9* |

**If the porosity is primary porosity use 9 ft/day, and if it is a combination of primary and secondary porosity use 15 ft/day.*

The default values fall within the acceptable range of published values (Fetter, 1988;Freeze & Cherry, 1979; Driscoll, 1989; U.S. EPA, 1994) and were based in part on data available for Ohio aquifers (Rau, 1969; Spieker, 1968, Ohio EPA Wellhead Protection Reports). Values at the low end of the acceptable range for porosity were chosen as defaults in order to provide more conservative (larger) protection areas, given a lack of site specific information for the aquifer. If grain-size analysis information is available for a specific aquifer the modeler can use that data and best professional judgment to adjust the porosity value in the model. If data on hydraulic conductivity is not available, it is also appropriate to model the public water system using a range of hydraulic conductivity values (based on acceptable range of published values for a given aquifer type) and then combine the delineated areas to form the protection area.

### 5.2 Determination of Flow Direction and Gradient

In areas that do not have existing potentiometric surface maps, other methods of estimating flow direction and gradient may be used. District staff may develop a potentiometric map from available well logs or resource characterization data, or if insufficient data exist in an area, estimate the flow direction based on topographic maps (for unconfined settings). If a public water system serves a population greater than 500, the modeler must attempt to determine the flow direction in the aquifer. Hydrogeologists should estimate flow direction and gradient as carefully as possible, given the existing data, and then decide which delineation method to use based on the level of certainty and other available data. Where there is insufficient data for even an estimate, hydrogeologists will have no choice but to use some variation of the volumetric equation.

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# APPENDIX A
# WhAEM and GFLOW Applications

The following is preliminary guidance on using WhAEM and GFLOW to delineate protection areas. It is not inclusive, and is meant to provide some “helpful hints” on using the program.

## Setting up the Model

**Boundary Conditions.** In alluvial or buried valley settings, if the hydraulic conductivity of the bedrock is at least two orders of magnitude less than the unconsolidated deposits, the valley walls can be modeled as no-flow boundaries (Anderson and Woessner, 1991). In cases where the bedrock is primarily shale, a no-flow boundary is a good assumption and WhAEM (or GFLOW) can be used. If the bedrock is a conductive sandstone, however, modeling a no-flow boundary may not be appropriate. In these cases, using the inhomogeneity features in GFLOW or developing a regional MODFLOW model may be necessary. For limestone or cyclothem bedrock situations, the district could use ground water resource maps to evaluate the potential yield of the bedrock. Low yielding and low conductivity areas probably do not contribute much water to the unconsolidated aquifer and can modeled as no-flow boundaries.

**Potentiometric Surface.** When using WhAEM or GFLOW, the modeler should first input the aquifer properties and boundary conditions, then use either the uniform flow option or input line-sinks (AEM option). The modeler should then run the model and evaluate the resultant potentiometric surface. If the surface is inappropriate the modeler should refine the model until it produces a good approximation of available potentiometric surface maps (P-Maps) or locally available head data. This should be done prior to inputting the pump rate of the well (unless the available potentiometric surface map was developed during pumping conditions).

**Multiple Aquifers.** Multiple aquifers are separated by aquitards that have a conductivity more than one order of magnitude lower than the adjacent aquifer. If a PWS has wells located in multiple aquifers, either a MODFLOW model can be developed or multiple WhAEM or GFLOW models can be developed. For example, in a buried valley setting that has an upper and lower aquifer an AEM model with linesinks can be created to model the unconfined aquifer, and the box method can be used to model the lower aquifer. The delineated areas could then be combined for the system’s protection area.

If the variation between conductivity is within the same order of magnitude the area may be able to be modeled as one aquifer using GFLOW. To use GFLOW add the transmissivity from the upper and lower aquifer and divide by the total aquifer thickness. To be conservative you should use the porosity value from the layer with the lower porosity.

## Near Field Versus Far Field

When setting up a WhAEM or GFLOW model be sure to surround the pumping wells with two “circles of line-sinks.” This means if you are placed in the wellfield and turn 360 degrees you should see at least two line-sinks or a no-flow boundary in every direction. Inhomogeneities do NOT count as no-flow boundaries. The far field line-sinks do not need to be as detailed (have as many vertices) as the near field line-sinks, however, they must be included in order to create the flow divides between adjacent aquifer systems. Far field streams should not be given streambed resistance values.

### Delineating Protection Areas
To delineate a protection area, double click on each well and select the "Other" tab. Checkmark (click) "Trace particle paths from well" and type the number of particles you would like to trace (for final delineation should use ~40 particles). Next, go to the "Model Settings" pull down menu and select the "Tracing" tab. Input your desired travel time (365 or 1825 days) and checkmark (click) "Compute particle paths." If you run the model and there are no pathlines you may need to change your starting elevation for the pathlines. To do this, double click on the well and select the "Other" tab. Enter the well screen elevation or the base of the aquifer under "Starting elevation" (this should solve your problem).

### WhAEM/GFLOW Modeling Options
A lot of questions have been raised on when it is appropriate to use the uniform flow option versus AEM. The options appropriate for various settings are outlined below:

- **Uniform Flow (Without Boundaries).** This option should only be used in laterally extensive aquifers that do not have flow boundaries near the wellfield.

- **Uniform Flow (With Boundaries).** Henk Haitjema and Vic Kelson (developers of WhAEM and GFLOW) indicated that using uniform flow with boundaries is not appropriate and should be avoided.

- **AEM (Unconfined Settings).** This option should only be used if the streams present near the wellfield are perennial, and are in good connection with the aquifer. This method should be used for public water systems with documented high levels of infiltration. The modeler should use one line sink (with multiple segments) near the wellfield. In GFLOW the district has the option of specifying nearfield resistance to the stream(s) and stream flow routing.

- **AEM- Box Method (Confined Settings).** This option can be used for confined settings (including confined buried valleys, confined bedrock aquifers, etc.). In confined valley settings, the valley walls should be modeled as no-flow boundaries (If the hydraulic conductivity in the valley sediments is two orders of magnitude or greater than the hydraulic conductivity in the valley walls). The constant head cells (uniform line sink) should be located far enough up-gradient to not intercept the protection area and should be based on a potentiometric surface map (See Figure C-1). In laterally extensive aquifers and aquifers with valley walls defined by inhomogeneities, no flow boundaries should be located far enough from the well as to not influence the shape of the protection area (See Figure C-2).

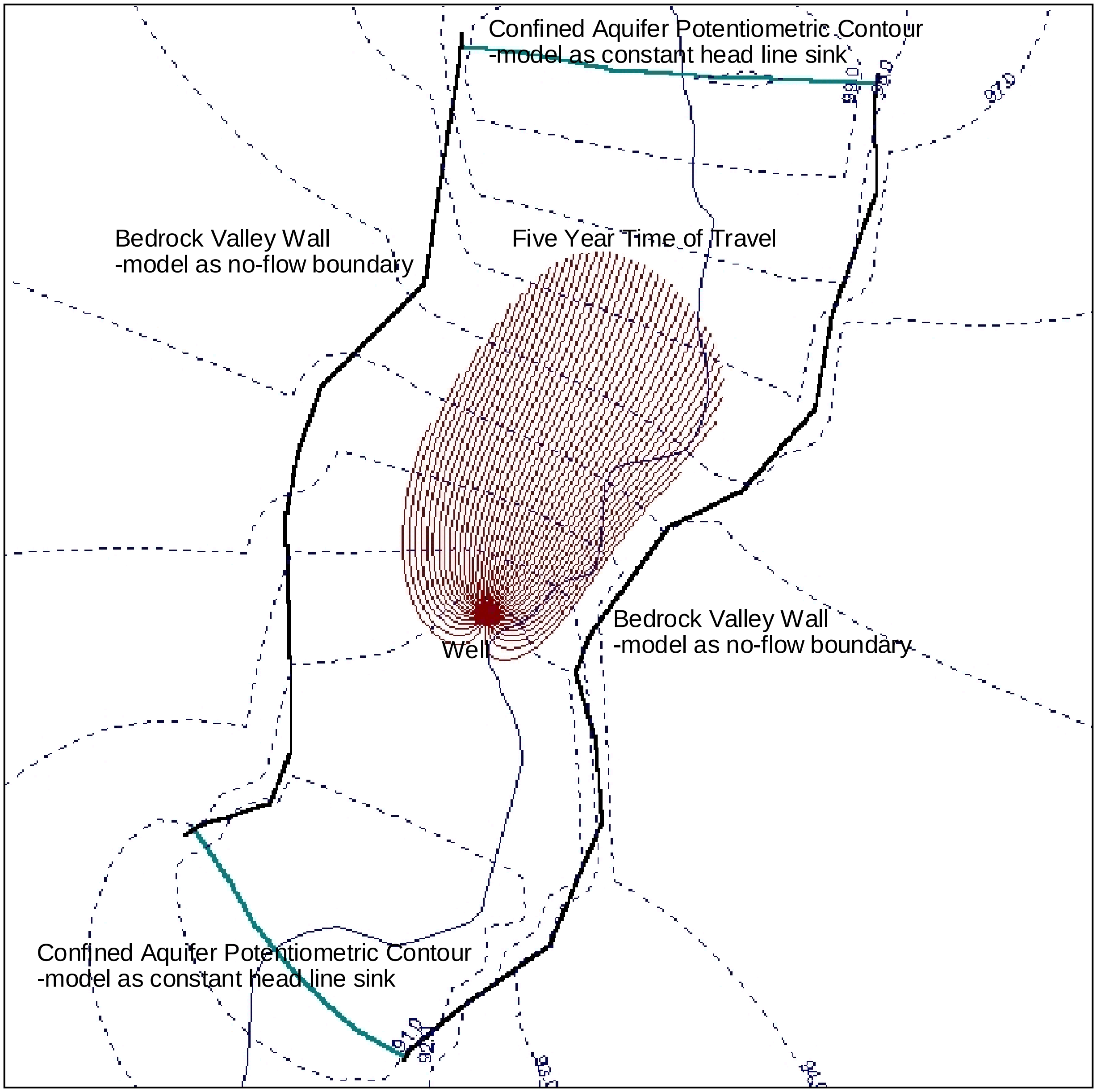


**Figure A-1.** Example of a GFLOW/WhAEM box-method delineation for a confined buried valley aquifer.

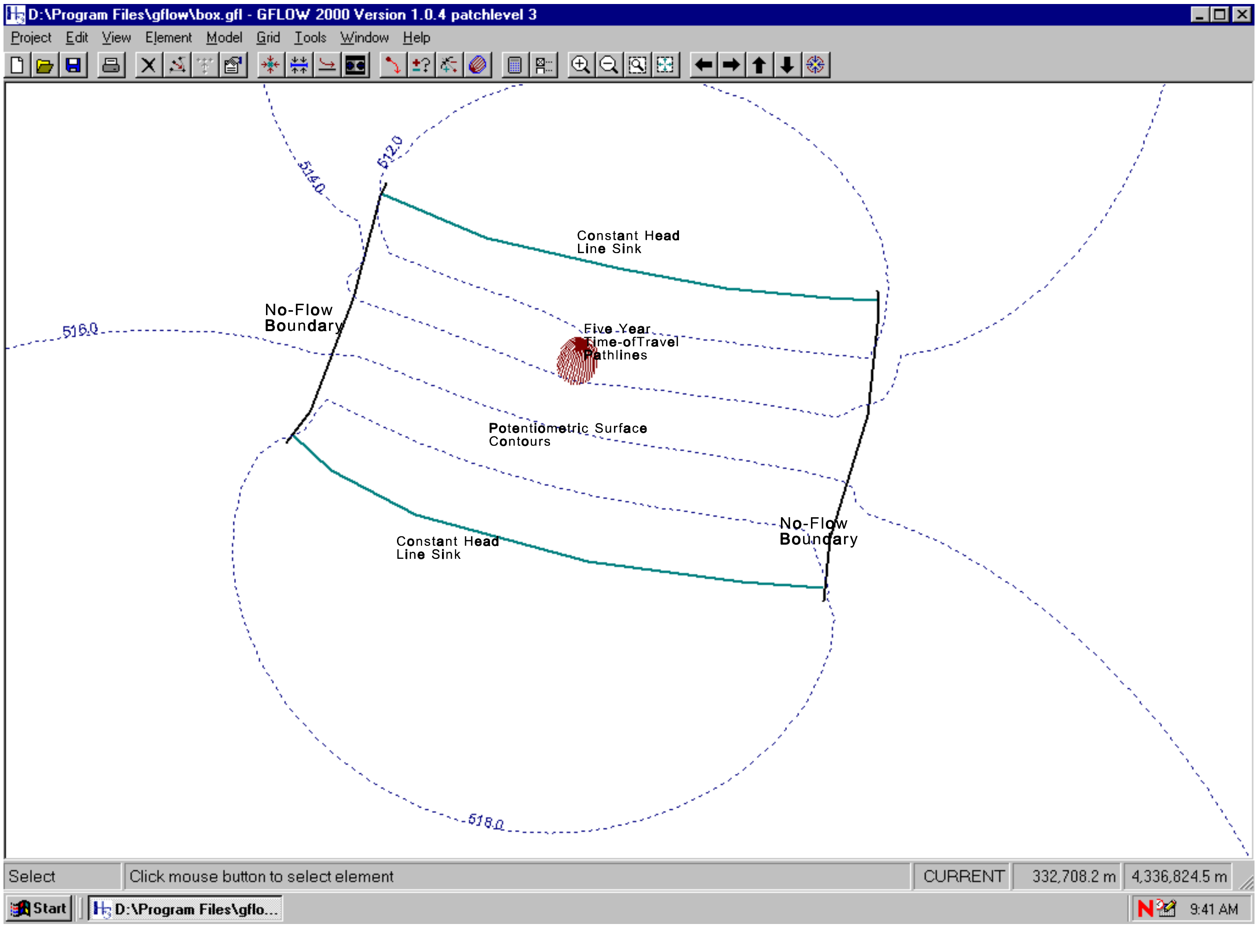


**Figure A-2.** Example of a GFLOW/WhAEM box-method delineation for a laterally extensive carbonate aquifer (no-flow boundaries are placed at an arbitrary distance from well.

# APPENDIX B
# GFLOW "Rules of Thumb"

(Modified from Henk Haitjema presentation)

**Adding Streams**

1. Resistance (layer thickness divided by conductivity of the layer)
    - Resistance should only be added to near field features.
    - Major rivers with sandy streambeds have resistance between 0 and 1 day.
    - Small streams with silty streambeds have resistance between 1 and 10 days.
    - Streams or lakes in till formations (overlying deep aquifers) have resistance up to 100 days
    - Resistance of 100 days or higher indicates almost no interaction with the aquifer.
2. Stream Width
    - Use actual stream width for small streams
    - Use line sinks on each side of a wide stream in the near field.
    - Width divided by resistance is conductance (ease with which water can enter the surface water body).
    - For wide streams and lakes the width defines the inflow/outflow zone near its boundary (you can use 10-20 feet and adjust the resistance rate accordingly).
3. Stream Depth
    - Depth is the estimated thickness of the resistance layer under the surface water plus the water depth (distance between water level in stream and bottom of streambed).
    - The depth parameter determines for which groundwater table elevation the surface water starts to "percolate."
    - The infiltration rate for a "percolating" surface water is independent of the head in the aquifer (water table elevation).
4. Stream Routing
    - Calculates baseflow from groundwater inflow, may add overland flow and headwater inflow to obtain total stream flow, limits infiltration of losing streams to available stream flow.
    - Only use streams in near field.
    - Select the stream flow routing option for each stream in the network and check "end stream" for the most downstream linesink. (GFLOW automatically links streams into network)

**Adding Inhomogeneities**

1. When conductivity and/or thickness vary.
    - Domains may be nested, but not overlap.
    - Domains should not have sharp corners.
    - Domains should have sufficient vertices.
    - A line-sink segment should either be inside or outside the inhomogeneity domain (A line-sink string may cross an inhomogeneity but a vertex needs to be place directly on the inhomogeneity so that each line-sink segment is either completely in or completely out of the inhomogeneity).

- Avoid inhomogeneity domains in the far field.
- Extra vertices should be added if the inhomogeneity is located near high capacity wells.

2. When only porosity varies.
   - Domain may have arbitrary large line-doublets.
   - Domain may overlap any other feature, including other inhomogeneity domains and line-sinks.
   - Domain may have any shape, including sharp corners.

### Horizontal Barriers (no-flow boundaries or leaky walls)

- Use to model slurry walls, rock outcrops, and low permeability zones that are two or more orders of magnitude less permeable than the surrounding aquifer.
- Barriers should not intersect or overlap.
- Open barriers (as used to model some valley walls) must have an increased vertex density towards their ends.
- Barriers with low resistance (e.g. high conductivity or partially penetrating) must have many vertices.
- Barriers may intersect inhomogeneities, but require extra vertices on both features near the intersection (better to avoid this).
- A closed impermeable barrier is a barrier with a zero conductivity and a bottom elevation at or below the aquifer bottom.
- A closed impermeable barrier defines two independent flow domains: an inside and an outside.
- The inside domain must have at least one head specified feature (also if "ignore inside region" is checked).

### Adding Particles

- The starting elevation for a particle used to delineate the five and one year time of travel needs to be set within (or close to) the screened interval of the well or aquifer base. If the elevation is too high or too low the particle paths will not be traced because the model may not have water at that elevation.

### Additional Information

Additional information on GFLOW and WhAEM can be found in the program documentation files, help files, and in the GFLOW training handouts provided by Henk Haitjema to Ohio EPA.